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OPTIMIZATION OF THE PARAMETERS FOR OPERATION AND VALVE DESIGN OF A TANK-CHARGING OXYGEN COMPRESSOR

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ABSTRACT

A combination of a tank-charging oxygen compressor simulation model and an optimization theory was used to predict enhanced oxygen compressor performance and oxygen quality and to improve the parameters for operation and valves design.

The paper illustrates a method for choosing constraints condition and designing parameters, and provides the optimal calculation program. Thus not only were manipulated to achieve a minimum value of oxygen compressor power attenuation and oxygen quality assurance, but working reliability and economy of an oxygen compressor have improved greatly.

INTRODUCTION

Tank-charging oxygen compressors are used in industries, such as metallurgy, aviation and space, and machinery etc. Now about 4000 tank-charging oxygen compressors are operating in China, and most of them process oxygen from separators, then the gas has to be compressed to 15MPa through oxygen compressors with spray colling and lubricating. Because oxygen contacts with water in a cylinder directly, some harmful influences are taken to the oxygen. Such as making weld ware quality bad and oxygen tank corrosion, shorting the service life of the oil in crankcase and declining the working reliability and economical interest of the oxygen compressor. High purity, low prince and water-free oxygen is demanded, the problem about improving working reliability and economical interest of the oxygen compressor must be solved in commercial and industrial application as soon as possible.

The paper illustrates working processes of a tank-charging oxygen compressor and utilizes some optimization theory. Though studying to the operating and the valve designing parameters of the tank-charging oxygen compressor, the problems about oxygen compressor and quality of oxygen have been solved. In optimization process, we choose the power per unit volume of fluid delivered as objective function. Pressure ratios, cylinder diameter ratios, rotation speed, stroke and the valve designing parameters are taken as designing parameters of an oxygen compressor. Relations between the objective function and the designing parameters have been studied comprehesively. The best combination of a set of independent designing variables is calculated through a mathematical model of the oxygen by a digital computer.

With an experimental facility, the values calculated by the model and the experimental values are closely agreement with each other and the deviation is below 5%. The quality of oxygen and the working reliability and economical interest of the oxygen compressor have been improved greatly.

MATHEMATICAL MODEL FOR OPTIMIZATION

A mathematical model for optimization of a tank-charging oxygen compressor relates to a series of designing parameters X of the oxygen compressor, which can make values of an objective function F(x) minimum under some definite constraints. It may be represented as

$$\begin{aligned} &\min f(x) \\ &\text{s.t. } G_i(x) \geq 0 \qquad i=1,2,\ldots m \\ &H_j(x) = 0 \qquad j=1,2,\ldots L \end{aligned} \tag{1}$$

1. Designing Parameters

Designing parameters of a valve involve a series of parameters which have close relation with the valve motion characteristics, and they are valve disc thickness X_1, valve port diameter X_2, valve lift X_3, valve disc diameter X_4, valve spring stiffness X_5 and valve spring perload X_6. If a compressor valving system is comprised of one suction and one discharge valve, then 12 independent variables have to be considered. For a 3 stage tank-charging oxygen compressor, 36 independent valve variables have to be considered. They may be represented by a vector as:

$$X = (x_1, x_2, \dots x_n) \qquad n = 1, 2, \dots 36 \tag{2}$$

where $x_1 - x_{12}$ the parameters of the first stage suction and discharge valve.

$x_{13} - x_{24}$ the parameters of the second stage suction and discharge valve.

$x_{25} - x_{36}$ the parameters of the third stage suction and discharge valve.

Both of pressure ratios ε_i and cylinder diameter ratios are main designing parameters, and since optimization of an oxyen compressor is often done under a definite delivery capacity and other conditions, so the correlation between pressure ratios and cylinder diameter ratios is a correlative function. If pressure ratios ε_i are taken as independent variables, the cylinder diameter ratios β_i can be calculated with formula (3) and (4).

$$\beta_1 = \sqrt{\frac{\lambda_2}{\lambda_1} \frac{T_{s1}}{T_{s2}} \frac{\xi_{s2}}{\xi_{s1}} \varepsilon_1} \tag{3}$$

$$\beta_2 = \sqrt{\frac{\lambda_3}{\lambda_1} \frac{T_{s1}}{T_{s3}} \frac{\xi_{s3}}{\xi_{s1}} \varepsilon_2} \tag{4}$$

$$\varepsilon_3 = \varepsilon / \varepsilon_1 / \varepsilon_2 \tag{5}$$

where $\beta_1 = D_1/D_2$, $\beta_2 = D_2/D_3$

D_i cylinder diameter of ith stage;

T_{si} suction temperature of ith stage;

ξ_{si} gas compressible coefficient of ith stage;

ε_i pressure ratio of ith stage;

ε overall pressure ratio.

The designing parameters of the tank-charging oxygen compressor are comprised of rotation speed n , stroke s and λ_L — the ratio of the crank radius to the connecting-rod length. These variables and the diameter of the first cylinder are correlative, i.e.

$$D_1 = \sqrt{\frac{4V_o}{\pi s n \lambda_L}} \tag{6}$$

where V_o swept volume of the cylinder.

In summary, a 3 stage tank-charging oxygen compressor is comprised of 41 designing parameters. They may be represented by a rector as:

$$X = (x_1, x_2, \dots, x_{36}, \varepsilon_1, \varepsilon_2, n, s, \lambda_L) \tag{7}$$

2. Objective Function

The purposes of optimization for a tank-charging oxygen compressor may be different, such as the reasonableness of the designing parameters, the cost of operation and manufacture etc. The paper is concerned with the cost of operation and manufacture and the service life of the compressor, therefore, we choose the power per unit volume of fluid delivered by oxygen compressor as the objective function, and the service life and the cost of manufacture and design as constraint conditions. When normalization is disposed, the objective function is represented as:

$$F(x) = \frac{N_i/N_o}{V/V_o} = \frac{1}{(N_o/N_i)(V/V_o)} \tag{8}$$

where V volume of fluid induced at suction condition;

N_i indicated cycle work;

N_o theoretical adiabatic cycle work.

3. Constraint Conditions

The choice of the constraint conditions of designing parameters is a key of the optimization for the tank-charging oxygen compressor. The paper has set up the reasonableness constraints, seeing table 1, through analyzing the reliability and economical interest of each parts. As far as machine modification is conerned, the main original parts of the oxygen compressor should be used as full as possible. Thus the modification time can be save and the cost decreased.

Since constrain conditions are different, the values of constrains could be quite different, thus constrains must be normalization in order to increase calculation sensitivity. The constrains are represented as:

$$\begin{aligned} G_i &= x_i - x_{io} \geqslant 0 \\ G_{i+1} &= x_{io} - x_i \geqslant 0 \end{aligned} \tag{9}$$

where x_{io} the maximum value of constrains;

x_{io} the minimum value of constrains.

MATHEMATICAL MODEL OF WORKING PROCESS IN A TANK-CHARGING OXYGEN COMPRESSOR

The model of the oxygen compressor is a formulation for solving objective function in optimization. The cylinder is handled as control volume,thus the equations of mass and energy conservation, valve open and close, and volume change may be expressed with mathematical formulas. Before the mathematical model of working processes is set up, some assumptions should be made as follow.

(1) The flow is steady adiabatic flow when oxygen enters or exits the cylinder.

(2) Working fluid within the control volume is uniform.

(3) Any outer action can be transmitted into working fluid within the control volume immediately.

(4) Compression and expansion processes are all adiabatic.

(5) Gas pulsation in suction and discharge cavities is neglected.

(6) Gas leakage through clearance between the piston rings and cylinder wall is neglected.

After above-mentioned assumptions are considered, a set of differential equations of the tank-charging oxygen compressor may be obtained through reasonably varying the equations of mass and energy conservation, valve open and close, and volume change. It can be represented as:

Suction Process

$$\frac{dp_i}{d\theta}=\frac{C_f\alpha_i A_{imax}}{V_{ci}\ \omega} kp_{s1}(\varepsilon_o\cdot\varepsilon_1\cdots\varepsilon_{i-1})\left(\frac{p_i}{p_{s1}\varepsilon_o\varepsilon_1\cdots\varepsilon_{i-1}}\right)^{\frac{1}{k}}\sqrt{\frac{2kR_iT_{si}}{k-1}\left[1-\left(\frac{p_i}{p_{s1}\varepsilon_o\varepsilon_1\cdots\varepsilon_{i-1}}\right)^{\frac{k-1}{k}}\right]}$$
$$-\frac{kp_i}{V_{ci}}\frac{dV_{ci}}{d\theta} \qquad (10)$$

$$\frac{dM_i}{d\theta}=\frac{C_f\alpha_i A_{imax}}{V_i\ \omega}\left(\frac{p_i}{p_{s1}\varepsilon_o\varepsilon_1\cdots\varepsilon_{i-1}}\right)^{\frac{1}{k}}\sqrt{\frac{2kR_iT_{si}}{k-1}\left[1-\left(\frac{p_i}{p_{s1}\varepsilon_o\varepsilon_1\cdots\varepsilon_{i-1}}\right)^{\frac{k-1}{k}}\right]}$$

$$\frac{dX_{[3+12(i-1)]}}{d\theta}=\frac{C_1A_{vi}(p_s\varepsilon_o\varepsilon_1\cdots\varepsilon_{i-1}-p_i)}{M_{vi}\,\omega^2\ X_{[3+12(i-1)]_{max}}}-\frac{X_{[5+12(i-1)]}\alpha_i}{M_{vi}\,\omega}-\frac{X_{[5+12(i-1)]}H_{oi}}{M_{vi}\,\omega\ X_{[3+12(i-1)]_{max}}}$$

$$\frac{d\alpha_i}{d\theta}=X_{[3+12(i-1)]} \qquad i=1,2,3$$

Discharge Process

$$\frac{dp_i}{d\theta}=-\frac{C_f\alpha_i A_{imax}}{V_{ci}\ \omega} kp_i\left(\frac{p_{si}\varepsilon_1\cdots\varepsilon_i}{p_i}\right)^{\frac{1}{k}}\sqrt{\frac{2kR_iT_{di}}{k-1}\left[\left(\frac{p_i}{p_{s1}\varepsilon_1\cdots\varepsilon_i}\right)^{\frac{k-1}{k}}-1\right]}-\frac{kp_i}{V_{ci}}\frac{dV_{ci}}{d\theta}$$

$$\frac{dM_i}{d\theta}=-\frac{C_f\alpha_i A_{imax}}{V_{ci}\ \omega}\left(\frac{p_{s1}\varepsilon_1\cdots\varepsilon_i}{p_i}\right)^{\frac{1}{k}}\sqrt{\frac{2kR_iT_{di}}{k-1}\left[\left(\frac{p_i}{p_{s1}\varepsilon_1\cdots\varepsilon_i}\right)^{\frac{k-1}{k}}-1\right]} \qquad (11)$$

$$\frac{dX_{[9+12(i-1)]}}{d\theta}=\frac{C_1A_{vi}(p_i-p_{s1}\varepsilon_1\cdots\varepsilon_i)}{M_{vi}\,\omega^2X_{[9+12(i-1)]_{max}}}-\frac{X_{[11+12(i-1)]}\alpha_i}{M_{vi}\,\omega}-\frac{X_{[11+12(i-1)]}H_{oi}}{M_{vi}\,\omega^2\ X_{[9+12(i-1)]_{max}}}$$

$$\frac{d\alpha_i}{d\theta}=X_{[9+12(i-1)]} \qquad i=1,2,3$$

When oxygen is compressed or expanded, $\alpha_i=0$, and the gas mass within the control volume unchanges, i.e $\frac{dM_i}{d\theta}=0$, thus a set of differential equations of compression and expansion are obtained.

Compression Process

$$\frac{dp_i}{d\theta}=-\frac{kp_i}{V_{ci}}\cdot\frac{dV_{ci}}{d\theta}$$

$$\frac{dM_i}{d\theta}=0 \qquad i=1,2,3 \qquad (12)$$

$$X_{[3+12(i-1)]}=0$$

$$\alpha_i=0$$

Expansion Process

$$\frac{dp_i}{d\theta}=-\frac{kp_i}{V_{ci}}\cdot\frac{dV_{ci}}{d\theta}$$

$$\frac{dM_i}{d\theta} = 0 \qquad (13)$$

$$X_{[9+12(i-1)]} = 0 \qquad i = 1,2,3$$

$$\alpha_i = 0$$

Where A_{imax} - maximum flow area of valve gap

C_f - flow coefficient of valve gap

C_l - lift coefficient of valve

k - adiabatic index

H_{oi} - precompression valve of valve spring

M - gas mass

M_{vi} - valve plate mass

p_{si} - suction pressure

R_i - gas constant

T_{si} - suction temperature

V - specific volume

V_{ci} - volume of cylinder

θ - crank angle

ω - angular speed

NUMERICAL COMPUTATION OF WORKING PROCESSES OF AN OXYGEN COMPRESSOR

Above differential equation system can be solve with Runge-Kutta Method when boundary conditions are given. The outer dead center is taken as start point. The pressure, mass, tempressure in the control volume, and the valve lift and velocity are calculated at any crank angle θ, till expansion process ends. Other processes are same in calculation method, but they use different equations.

The start and the end points may be not same for each stage, but only when the relative error of two points is smaller than a given allowance, the iteration process can be terminated. Otherwise, we will continue to calculate with average value of the two points as a start point until the relative error becomes smaller than the given allowance.

The objective function can be obtained for a set of designing parameters X through numberical calculation. It may represented as:

$$N_i = \frac{n}{60} \oint V_{ci} dp$$

EXAMINING FOR MATHEMATICAL MODEL OF WORKING PROCESSES IN THE TANK-CHARGING OXYGEN COMPRESSOR

Satisfactory optimization values are dependent on whether model is correct or wrong. An experiment has been carried out for examining the mathematical model. The experiment has been done on a 3 stage tank-charging oxygen compressor (Z-100/150). Figure 1 shows compare of the values of calculation and experiment in an indicator diagram. Figure 2 shows curve of valve lift. Table 2 shows valurs of calculation and experiment of the oxygen delivery and indicated power. Thus it can be known that the mathematical model of working processes can be used to predict compressor performance and study some influence from designing parameters on oxygen compressor working processes

OPTIMIZATION METHOD

Using a reasonable optimization method can not only save the calculation time, but also obtain satisfactor result of calculation. This paper utilizes SWIFT as calculation method according to the characteristics of the objective function, the number of designing parameters and the properties of the constraint conditions. Figure 3 shows curves of valve plate lift before and after optimization.

CONCLUSIONS

The mathematical method of a tank-charging oxygen compressor described in this paper is reasonable and correct according to experimental value on a 3 stage oxygen compressor. The model can be used to predict the influence on performance of oxygen compressor from design parameters and enhance the working reliability and economical interest of the oxygen compressor. The optimization result of valve designing parameters and compressor structure parameters with this program are satisfactory. With this optimization method, we don't need the spray water cooling for a tank-charging oxygen compressor, and the oxygen quality can be improved greatly. It can be predicted that the optimization design would come into wide use for design and modification of oxygen compressor.

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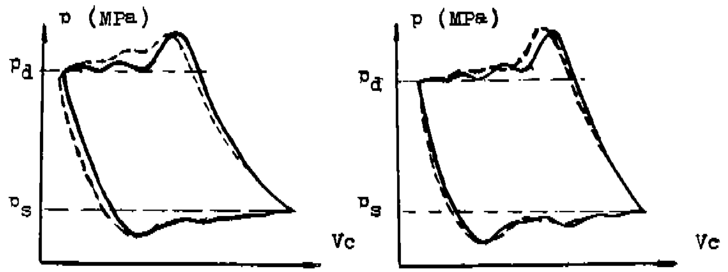
Table 1 Valves parameters constraints

Valve parameters		Unit	Suction valve	discharge valve
disc thick-ness	1th 2th 3th	mm	$1 \leq \begin{pmatrix}x_1\\x_{13}\\x_{25}\end{pmatrix} \leq 3$	$1 \leq \begin{pmatrix}x_7\\x_{19}\\x_{31}\end{pmatrix} \leq 3$
port diame-ter	1th 2th 3th	mm	$5 \leq \begin{pmatrix}x_2\\x_{14}\\x_{26}\end{pmatrix} \leq \frac{1}{3}D_i$	$5 \leq \begin{pmatrix}x_8\\x_{20}\\x_{32}\end{pmatrix} \leq \frac{1}{3}D_i$
plate life	1th 2th 3th	mm	$1 \leq \begin{pmatrix}x_3\\x_{15}\\x_{27}\end{pmatrix} \leq 4$	$1 \leq \begin{pmatrix}x_9\\x_{11}\\x_{33}\end{pmatrix} \leq 4$
disc diame-ter	1th 2th 3th	mm	$8 \leq \begin{pmatrix}x_4\\x_{16}\\x_{28}\end{pmatrix} \leq \frac{D_i}{3}+3$	$8 \leq \begin{pmatrix}x_{10}\\x_{22}\\x_{34}\end{pmatrix} \leq \frac{D_i}{3}+3$
	1th 2th 3th	$N/_{m^2}$	$\begin{pmatrix}x_5\\x_{17}\\x_{29}\end{pmatrix} \geq 0$	$\begin{pmatrix}x_{11}\\x_{23}\\x_{35}\end{pmatrix} \geq 0$
spring per-load	1th 2th 3th	N	$\begin{pmatrix}x_6\\x_{18}\\x_{30}\end{pmatrix} \geq 0$	$\begin{pmatrix}x_{12}\\x_{24}\\x_{36}\end{pmatrix} \geq 0$

Table 2 Values of calculation and experiment of the delivery capacity and indicated power

Operating parameters				delivery capacity (M^3/h)			indicated power(kw)		
p_s (MPa)	p_d (MPa)	n (r/min)	s (mm)	calculation	experiment	deviation	calculation	experiment	deviation
1.0	15	180	180	182.9	180.4	1.37%	19.5	20.4	-4.6%



a) first stage b) third stage

FIG. 1 compare of the values of calculation and experiment in an indicator diagram

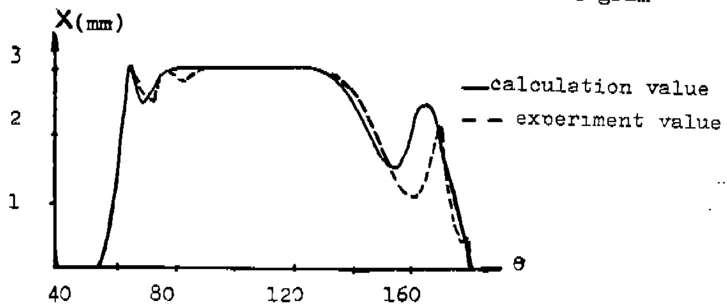
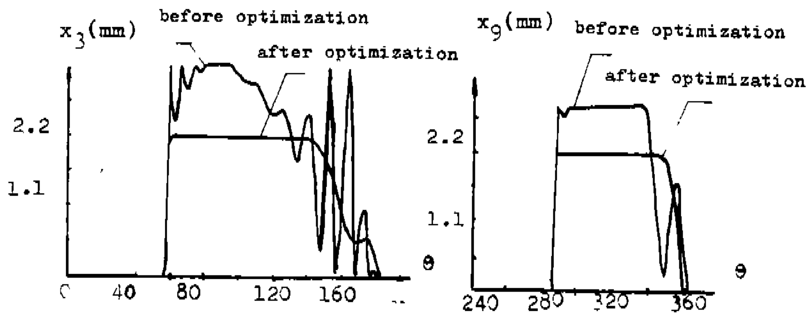
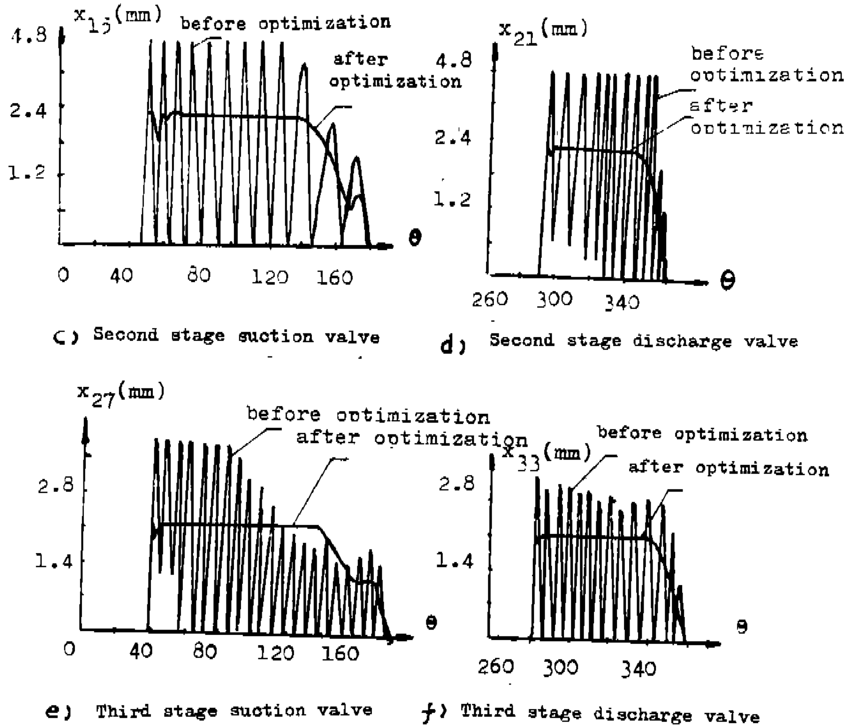


FIG.2 curve of valve lift



a) First stage suction valve b) First stage discharge valve



c) Second stage suction valve

d) Second stage discharge valve

e) Third stage suction valve

f) Third stage discharge valve

FIG. 3 curve of valve plate lift before and after optimization